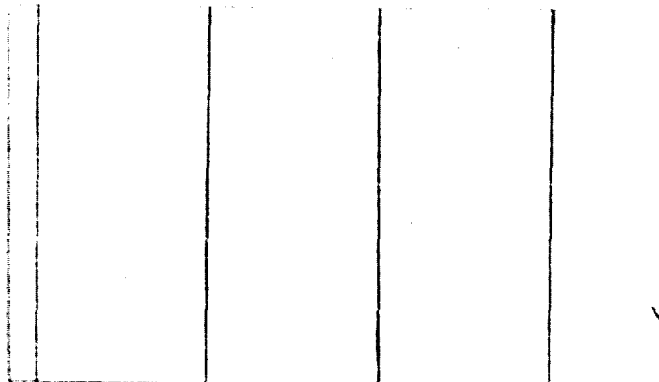# General Disclaimer

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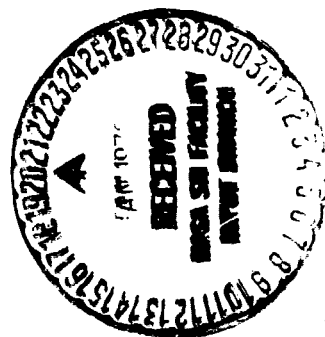
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SURVEY OF HYDROGEN PRODUCTION
AND UTILIZATION METHODS

Volume 1. Executive Summary

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EXECUTIVE SUMMARY

Introduction and Objectives of the Study

Hydrogen has been widely discussed and considered as a potential fuel. As traditional fossil fuels become scarce and more expensive, increased reliance must be placed on nonfossil sources such as nuclear and solar energy. One way of using these energy sources (i.e., converting them to electricity) is receiving much emphasis in industrial and government programs. Conversion of these nonfossil sources to hydrogen and use of this combustible fuel gas to deliver energy is an attractive alternative. In the United States, our present major source of hydrogen is natural gas, which is becoming increasingly more expensive and scarce. In the near term, therefore, hydrogen from the abundant fossil fuel, coal, could become important for specialty fuel and commodity purposes.

The utilization of hydrogen, if hydrogen is considered for use as a fuel, will be somewhat different than that of conventional fuel gases. Certain changes will probably have to be made in conventional fuel delivery systems and in utilization equipment to allow them to handle hydrogen.

The possible use of hydrogen as a synthetic fuel is the conceptual framework on which this study is based. The study includes a review of the known methods for producing hydrogen, with emphasis on those methods that use nuclear or solar energy; and it includes a review of the present and potential uses for hydrogen, both as a fuel and as an industrial feedstock.

Specifically, the objectives of the study were —

● To identify and evaluate all developed processes for the production of hydrogen and to assess any novel or unconventional methods identified during the study

● To analyze the feasibility of hydrogen production by several different methods that are currently under development

● To review the present and potential uses for hydrogen as a fuel for residential and industrial applications and as a chemical feedstock

● To recommend a series of research and development projects, to be undertaken during the next 5 years, to assess the feasibility of hydrogen for energy delivery and to develop attendant technology

● To provide an estimate of the cost of the R & D program planned for the next 5 years.

The study specifically excluded a detailed review of processes for the production of hydrogen from coal, including only a report on the parallel study of hydrogen from coal under way at the Institute of Gas Technology (IGT) for the National Aeronautics and Space Administration (NASA)-Langley Research Center. The use of hydrogen as a fuel for transportation was also specifically excluded from the scope of the study. Potential additional demands for hydrogen by these fuel markets should be kept in mind as the report is reviewed.

Energy Supply and Demand Models

Before embarking on the main thrust of the study, a review was made of U.S. energy supply and demand projections to assess the quantities of hydrogen that would be required to make significant contributions to the U.S. energy picture. This was done so that some of the potential production methods, to be studied in other tasks, could be put in perspective with respect to meaningful scales of production.

No energy demand and supply projection is considered to be wholly accurate, and any such model we used was likely to be challenged. To try to overcome this problem, two energy models were developed — one optimistic and one pessimistic — in an attempt to delimit the range of future possibilities.

It is assumed in Model I (optimistic) that the energy supply will be based on the post-1973 energy picture, which assumes limited availability of imported oil, but maximum development of domestic resources, including synthesized fuel. In Model I it is also assumed that, in the future, all market sectors will receive a percentage of the total energy supply that differs only slightly from current percentages. The market sectors are residential/commercial, industrial, electricity generation, other uses, and transportation (included for completeness). Market-sector-demand growth rates for the period from 1970 to 1985 are patterned after the "low level of demand" presented in the authoritative National Petroleum Council (NPC) report for 1973, U.S. Energy Outlook. For this model and during this period, the annual growth in total energy demand falls from about 3.5% to about 3.3%. We extrapolated this low-level-demand projection to the year 2000 and used an average annual growth rate of about 2.8% for the period from 1985 to 2000. Specific growth rates for individual market sectors were assumed. In this model, the

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electricity-generating sector grows at a rate necessary to supply the other sectors, but this rate does not exceed 6.5%/yr for electricity for the residential/commercial sector and 6.0%/yr for supplies to the industrial sector.

It is assumed in Model II (pessimistic) that the energy supply will be based on the pre-1973 world energy picture, which assumes growing energy importation and only moderate development of synthetic fuels from coal and shale. Similar to Model I, Model II assumes that all market sectors will receive a percentage of the total energy supply that differs somewhat from the present situation. Market-sector-demand growth rates for the period from 1970 to 1985 are patterned after the "high level of demand" also presented in the abovementioned NPC report. For this model and during this period, the annual growth in total energy demand falls from about 4.5% to about 4.3%. We extrapolated this high-level-demand projection to the year 2000 and used an average annual growth rate of 3.8% for the period from 1985 to 2000. Specific growth rates for individual market sectors were assumed. The electricity-generating sector again grows at a rate necessary to supply the other sectors, but this rate does not exceed 7.0%/yr for electricity for the residential/commercial sector and 7.5%/yr for supplies to the industrial sector.

Both models show energy deficits for some years that must be filled either by imports or by an energy carrier (like hydrogen) produced from a previously undedicated energy source. Thus, the models can be used to show the maximum use that could be made of hydrogen (excluding automotive transportation), should a decision be made to make as much use of hydrogen as possible. The models also show the quantity of raw energy, over and above traditional uses, that would potentially be available for the manufacture of hydrogen, other synthetic fuels, or electricity.

To arrive at an estimate of the maximum potential demand for hydrogen, we added the shortfalls of the appropriate market sectors to determine the potential demand for an additional fuel. The demand for additional fuel could be satisfied by hydrogen from potentially "excess" nuclear heat or by hydrogen produced from additional fossil resources or from "new" energy sources. These new energy sources include solar heat, waste materials, nuclear fusion, wind power, geothermal heat, and ocean thermal gradients. Energy

imports from foreign countries were not included in the energy supplies for the market sectors and, if incorporated, would reduce the potential demand for hydrogen.

The bounds for the maximum hydrogen demand and for the potential "excess" coal and nuclear power and the quantities of hydrogen that could be synthesized from this potential "excess" energy are shown in Table ES-1. This table does not imply that the technology either to produce or to use the hydrogen in this quantity will be available by the date shown.

Table ES-1. BOUNDS OF POTENTIAL MAXIMUM DEMAND AND SUPPLY OF HYDROGEN

	1980	1990	2000
	$\longleftarrow$ 10^{15} Btu $\longrightarrow$		
Hydrogen Demand	7.3[*]-19.1[†]	7.2[*]-33.0[†]	17.7[*]-43.5[†]
"Excess" Raw Energy	5.0-2.1	19.6-2.0	28.2-0.0[‡]
Potential Hydrogen Supply	1.5-0.6	6.1-0.7	10.0-0.0

[*]Model I quantities on left.

[†]Model II quantities on right.

[‡]Actually a deficit.

In Table ES-2 we show estimates, based upon the extrapolation of historical data, of the markets that could exist for hydrogen. These estimates were made without reference to either Model I or II and show only those utilization areas that could, with some modifications in procedure or equipment, be switched to competively priced hydrogen.

Examination of Table ES-2 shows that although there will be a growing market for hydrogen as a feedstock in chemical processes and a large new market for hydrogen as a feedstock in synthetic fuel processes, the largest potential demand for hydrogen will be as a supplement to, or a replacement for, natural gas. The quantities involved in this last sector are so great that cnly processes with very large production capabilities should be considered.

General Survey of Hydrogen Production Methods

In this study we surveyed the following methods for producing hydrogen:

● Conventional steam reforming or partial oxidation of hydrocarbon fuels (natural gas and oil)

- Advanced processes for the production of fuel or industrial-grade hydrogen from coal

- Electrolysis of pure and impure water

- Thermochemical methods of splitting water

- Photochemical and related concepts for production from water

- Other miscellaneous concepts including direct thermal dissociation of water, radiolytic decomposition of water, and processes to make hydrogen from waste materials.

Table ES-2. DEMANDS FOR COMPETITIVELY PRICED HYDROGEN

	1980	1990	2000
		10^{15} Btu/yr	
Ammonia Synthesis	0.49	0.80	1.20
Chemical Methanol	0.11	0.20	0.36
Hydrocracking Crude Oil	0.18	0.15	0.27
Hydrotreating Crude Oil	0.13	0.20	0.18
Direct Reduction	0.10	0.36	0.65
Other	0.10	0.20	0.34
Synthetic Fuels			
SNG	0.09	1.45	3.74
Coal Liquefaction	0.00	0.84	2.86
Shale Oil	0.00	0.16	0.41
Subtotal	1.20	4.36	10.01
Gaseous Fuel	3.30	14.50	24.00
Total	4.50	18.86	34.01

The first class of processes was dealt with in a brief and descriptive manner because these processes cannot, in the long run, justify research to improve them, nor (because of the shortage of feedstocks) will they find a growing place in hydrogen production technology. The production of hydrogen from coal was addressed briefly because a parallel study was under way for the NASA-Langley Research Center. Most emphasis was placed on the electrolytic, thermochemical, and photochemical methods for hydrogen production. In addition, a thorough search of the patent literature back to 1917 was made to uncover hydrogen-production processes worthy of development in the light of present energy economics.

Production of Hydrogen From Natural Gas and Oil

The steam reforming of natural gas is a well-established and the most widely used process for manufacturing hydrogen in the United States. The

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primary processing step is the reaction of methane with steam on a nickel-oxide catalyst to produce carbon monoxide and hydrogen. This mixture is then "shifted" (reacted with excess steam on a second catalyst) to convert the carbon monoxide to carbon dioxide, thus producing more hydrogen. The resulting gas is then compressed and scrubbed to remove the carbon dioxide, and the final traces of carbon oxides are removed by catalytic methanation. Hydrogen, typically 97% pure, is produced at an overall energy efficiency of about 68%.

Two very similar partial-oxidation processes for the conversion of liquid hydrocarbons to hydrogen have been commercialized. These are the Texaco Process and the Shell Gasification Process. Heavy oil is reacted with steam and oxygen at a high pressure, and the resulting gas is rapidly quenched with water. The resulting mixture of carbon monoxide, water vapor, and hydrogen is subsequently shifted and scrubbed to yield industrial-grade hydrogen. Both of these processes are well developed and need little research to bring about improvements.

Production of Hydrogen From Coal and Water

As part of the NASA-Langley Research Center project being conducted by IGT, process designs for the conversion of coal to high-purity hydrogen were prepared. Plant capacities were sized to give total product heating values of 250 billion Btu/day. (Such a plant would consume from 15,000 to 20,000 tons of coal per day.) This capacity is typical of the standard methane- or pipe-line gas-from-coal plant and is considered to be beyond the point at which economy of scale is significant.

The processes were purposely selected to represent a variety of modern technologies. Process designs have been made in sufficient detail to permit determination of overall plant efficiencies on a comparable basis. In addition, capital and operating costs for one of the processes were estimated. The selected processes are —

● The Koppers-Totzek Process, a commercially available process based on the suspension gasification of pulverized coal by steam and oxygen at essentially atmospheric pressure under slagging conditions in excess of 3000°F. This type of gasifier has most commonly been used for ammonia synthesis. A hydrogen-production facility would utilize the same gasifying principles, but would require different downstream process operations.

• The U-GAS™ Process, which is currently undergoing process development in a fluidized-bed gasifier. The operating pressure is substantially above atmospheric, 3000 psig being typical. Gasification occurs in the presence of steam and oxygen, but under nonslagging conditions at a temperature of 1900°F. The U-GAS Process is intended primarily to produce a low-Btu utility fuel gas; but, in conjunction with an appropriate purification train, can be used to produce pure hydrogen.

• The Steam-Iron Process, a modern, continuous version of the old batch method of generating hydrogen. Coal is first gasified by steam and air in a fluidized bed at 1900°F to make a producer gas that contains carbon monoxide. This gas is used to regenerate iron oxide that, in the reduced state, decomposes steam in a separate vessel to provide hydrogen. The iron oxide is circulated between the oxidizer (the hydrogen-generation vessel) and the reductor. Because the hydrogen is not derived from the producer gas, the nitrogen entering with the air in forming the producer gas does not contaminate the product. The process is designed to operate at a pressure of 350 psi.

The above processes produce hydrogen ranging in purity from 93% to 96%, the impurities being nitrogen and methane.

The calculated efficiencies, based on the coal feed of the three processes, range between 45% for steam-iron (59% with credit for by-product electricity) and 66% for U-GAS. Hydrogen produced by the U-GAS Process from coal at $0.30/million Btu would cost about $2.17/million Btu.

Electrolysis

Electrolysis occurs when a direct electric current is passed through a conducting water solution (usually an alkali) between two electrodes. Water molecules are decomposed to produce hydrogen at one electrode and oxygen at the other. The advantages of the electrolytic method of hydrogen production are that hydrogen and oxygen are directly separated in the process and that the electrolyzer is a relatively simple piece of equipment with no moving parts. Some disadvantages of electrolysis are that the process needs a high-quality energy supply (in the form of electric power) and that to operate efficiently, the electrolyzer has to be of a very sophisticated design.

The rate of hydrogen production by an electrolyzer is directly related to the current that flows through the cell; but the energy consumption, and thus the overall efficiency, is related to the voltage needed to run the cell at a reasonable rate. The theoretical voltage at which water decomposes to hydrogen and oxygen at 1 atm and 25°C is 1.23 volts. In practice, higher

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voltages must be applied to supply the reaction entropy (about 0.25 volt) and irreversibilities (which typically account for an additional 0.5 volt). Typical industrial cells operate at about 2 volts, which corresponds to a thermal efficiency of about 75%.

There are two principal types of cell construction. In the tank-type cell, the electrolyte is contained in a large vat or tank, and electrodes are hung from the lid. Alternate electrodes are connected to positive and negative bus bars, and asbestos diaphragms are hung between the electrodes. Hydrogen and oxygen, evolved at alternate electrodes, are ducted away by suitable manifolding arranged in the lid of the tank. All the positive electrodes in one tank are connected together in parallel, as are all the negative electrodes, so the voltage across one tank is only about 2 volts. It is usual for several tanks to be connected together in series.

In the "filter-press" or stack-type construction, electrodes and diaphragms are stacked together alternately and are connected electrically in series. The electrolyte is contained in the cavities between the electrodes, sealed with peripheral gaskets. Hydrogen and oxygen are ducted away in suitable manifolds, and the electrolyte is usually circulated through the cells in parallel. In this type of cell, the voltages are additive from one cell to another.

It is important to realize that a given electrolyzer cell can produce hydrogen at a wide range of production rates, depending on the applied voltage. Thus, there is a trade-off between the hydrogen-production rate and the efficiency at which the cell is operated. Theoretically, production of hydrogen at a high pressure requires more energy. However, within limits, some commercial electrolyzer cells can operate closer to the theoretical voltage, and therefore more efficiently, at higher pressures.

During the course of this study, eight commercial manufacturers of electrolyzers were surveyed either by personal visits or through correspondence. In addition, two chemical companies that manufacture and operate their own cells supplied limited information. It is noteworthy that a) manufacturers of the larger installations of electrolyzers are located in Europe and not in North America, b) very few of the manufacturers produce cells capable of delivering hydrogen at pressure, and c) most of the manufacturers prefer the stack or filter-press design to the tank type.

From the data provided by the manufacturers, we were able to calculate the cost of electrolytically produced hydrogen as a function of the electric power costs. (See Figure ES-1.) Our costs are derived from the capital costs and the polarization curve provided to us by the manufacturers, using the same financial model in each case. The cost calculation method is typical of those used by utility industries. Because of the financial models used to derive the hydrogen costs, our hydrogen costs m .y differ somewhat from those claimed by the individual manufacturers. Cost data sufficient to construct the family of curves shown in this figure were supplied only by Lurgi GmbH; Teledyne, Inc.; and General Electric Co. (GE). Note that the GE figures are projected data, but that Lurgi and Teledyne electrolyzers are already in production.
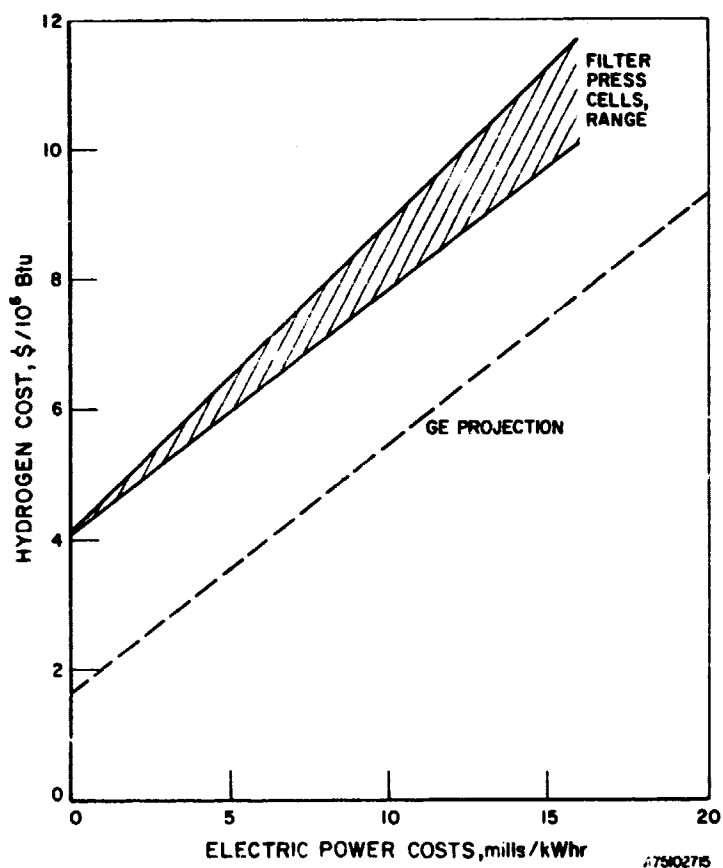

Figure ES-1. HYDROGEN PRODUCTION ECONOMICS

Four large industrial electrolyzer plants are currently producing, from hydroelectric power, hydrogen for use in ammonia production. The plants are located in Norway, Canada, Egypt, and India. In addition, many smaller

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units are located in almost every country of the world. These smaller units are used in applications for which high-purity hydrogen is required. Electrolysis is by no means the major method for producing hydrogen, but it is a technology that is used to a significant extent in industry.

The electrolyzer industry is not big enough to be able to sustain through internal funds a research program of the size that would bring about significant improvements. GE is the only company working on electrolyzers that use an ion-exchange resin or a solid-polymer electrolyte. All other research programs surveyed use aqueous alkaline electrolytes. Most research programs are directed toward increasing the efficiency and reducing the capital costs of electrolyzer systems.

Electrolysis of impure water and of sea water will lead to the serious problems of corrosion of cell components, blockage of the cells with residues, and production of chlorine (from sea water) along with oxygen at the anode. There appears to be little incentive to research these problems because the cost of water purification, both on an energy and an economic basis, represents only a small fraction of the overall cost of converting energy to hydrogen. Purification of water to boiler-feedwater quality standards will require only about 10% of the energy subsequently needed to electrolyze the water. Because this purification energy is usually in the form of low-grade heat, its cost is between 2% and 5% of the overall hydrogen-production cost.

Thermochemical Water Splitting

Thermochemical hydrogen production is a means of splitting water into its elements, hydrogen and oxygen, through a series of chemical reactions. All chemical intermediates are recycled internally within the process so that water is the only raw material and hydrogen and oxygen (separated) are the only products. Heat constitutes the primary energy input. Much research is now in progress on this type of reaction sequence because thermal-energy inputs derived from solar or nuclear energy could potentially be converted to chemical energy (hydrogen) by this method at fairly high efficiencies.

The following reaction sequence, an example of a thermochemical process, was postulated as early as 1924 by Collett in a British patent:

$$H_2O + Hg \rightarrow HgO + H_2$$
$$\underline{HgO \rightarrow Hg + 1/2O_2}$$
$$H_2O \rightarrow H_2 + 1/2O_2$$

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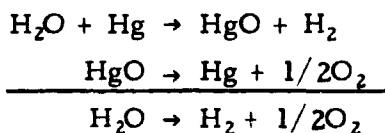
Thermochemical hydrogen-production processes are often viewed as alternatives to electrolysis. Both processes could use the heat from a nuclear reactor to make hydrogen, but while the electrolytic step in the nuclear heat-to-hydrogen sequence can be very efficient, the practical limitations of electricity generation make electrolytic hydrogen production an inefficient process overall. Generally, 20% of the primary heat energy is converted to hydrogen energy by a current-technology electrolytic process. One objective of thermochemical production is to avoid the low-efficiency electricity generation step.

The development of thermochemical hydrogen-production processes is in its infancy. Therefore, it is premature to report in detail on process parameters, engineering flowsheets, and cost analyses of specific processes. Large-scale thermochemical hydrogen production is probably at least 20 years away. This is reflected by the variety of research organizations doing work in the field and by the numerous approaches to this research.

During this study we interviewed 22 research groups who are, or were, recently, working on thermochemical hydrogen-production processes. Because of the proprietary nature of the many programs that are under private sponsorship, full disclosure of their work was impossible. Therefore, some of the cycles thought to be of high quality in terms of practicality and energy efficiency are not available for publication.

Because it is too early to evaluate thermochemical processes on a relative-cost basis, we used the next most important parameter — efficiency. During the study we examined several different definitions of overall process efficiency, and we selected both a definition and a means for deriving the efficiency of a multistep chemical cycle, which we recommend to NASA for comparison purposes.

Efficiency assessments should incorporate a process for selecting reaction temperatures, a material flow pattern, an internal heat utilization and enthalpy balance, an estimate of work requirements within the cycle, a calculation of work available from excess heat within the cycle, and a calculation of the energy efficiency. These calculations can be easily made if thermodynamic data are available and if they are based on reaction equilibria; on perfect heat transfer; and on the assumption that work requirements for gas-flow pressure drops, liquid pumping, and the transfer of solid materials are negligible. If the process for selecting operating conditions can be

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optimized using known thermodynamic data to minimize the overall energy input to the cycle, an efficiency so calculated will then be the maximum attainable efficiency for a process.

We recommend using the high heating value of hydrogen as a measure of the chemical energy output because this agrees with the overall thermodynamics of water splitting and is in line with the traditional practice of the natural gas industry. (The high heating value takes credit for the heat released in the condensation of the combustion-produced water vapor to a liquid.)

A general trend that a number of organizations have observed is that the fewer the chemical reactions within a thermochemical cycle, the higher the efficiency. There are then fewer heat-transfer steps, fewer gas separations, and fewer material-handling steps; and there is less of an overall system pressure drop. Also, a basic theoretical principle implies that other things being equal, processes with higher maximum heat-input temperatures exhibit higher overall efficiencies.

Another key parameter that is to be considered in evaluating thermochemical cycles is the corrosivity of the compounds in the cycle. Many of the proposed cycles have compounds that are extremely corrosive to common construction materials, and whether or not there are economically available materials that can contain the compounds without contaminating them is questionable. Therefore, materials that can withstand high temperatures and chemical attack are of utmost importance to thermochemical hydrogen production. However, reasonable materials research cannot commence until specific candidate cycles have been selected. Few research groups are yet ready to do this.

The efficiency of a thermochemical cycle is fundamentally dependent upon the temperature at which heat is available to it. Thermochemical processes that promise greater overall efficiencies than (future-technology) electricity generation plus electrolysis require very high temperature heat. A high-temperature, gas-cooled nuclear reactor might deliver heat from its core at from about 900° to $1000^{\circ}C$, which, after exchange into the process, is hot enough to drive an efficient thermochemical cycle. Other types of nuclear
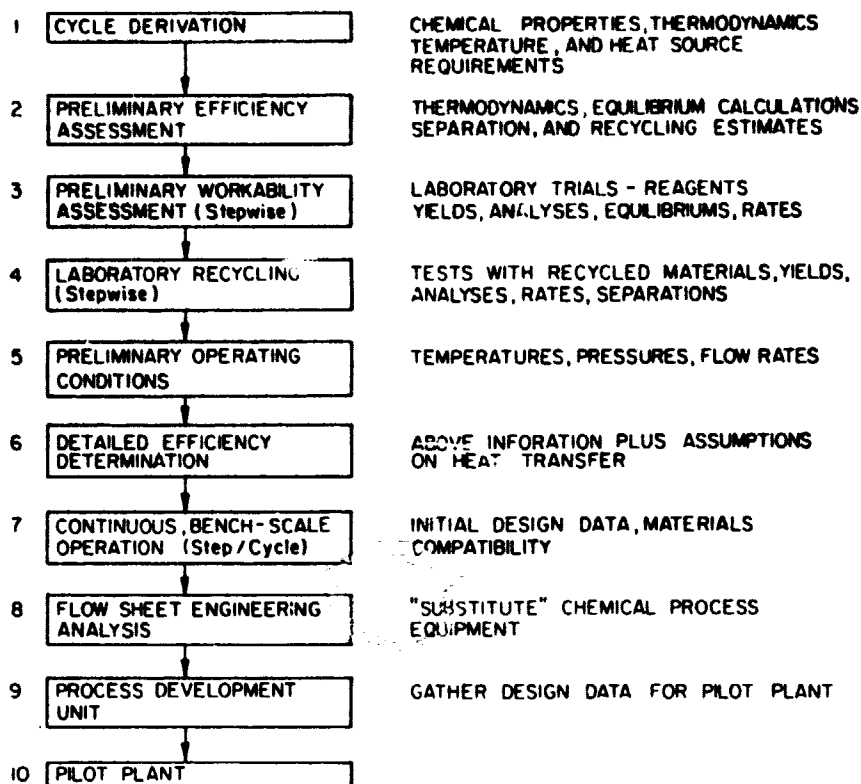
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reactors, which would deliver lower temperature heat (below about 700°C) to a process, cannot drive pure thermochemical cycles that promise efficiency advantages over electricity generation plus electrolysis.

To date, no experimental work has been done to apply solar-furnace technology to thermochemical hydrogen production, even though there is well-known and applicable solar-furnace technology for temperatures above 1000°C. Solar furnaces would have the apparent advantage of being able to supply heat at somewhat more isothermal conditions than do nuclear reactors. This is important because most thermochemical cycles require significant amounts of input heat for chemical reactions that occur at constant temperatures.

The technological development required for thermochemical hydrogen production, as an approximate consensus constructed after our interviews with the many research groups, is depicted in Figure ES-2. The series of stages in this figure is intended to portray an orderly development of the technology for thermochemical hydrogen production. On the average, the state of the technology for the various programs surveyed is at stage 3 or 4. While a few groups are still working at stage 1, a few others have progressed to stage 8; but this rapid progression has not included most of stages 4 and 6, and it has not included any of stage 7. (Some groups would prefer to put stage 7 after stage 8.) Most research groups interviewed placed attainment of stage 10 at 1985 or later; and most at stages 3 and 4 placed attainment of stage 7 at from 3 to 5 years distant (1978 to 1980) with annual funding requirements of from $500,000 to $1 million, provided that one single cycle be selected now for concentrated effort. Most groups, however, are not yet prepared to single out a "best" cycle.

Photosynthesis

In its simplest form, the photosynthesis process consists of a water-splitting reaction under the influence of light and chlorophyll. Water is split into a reducing species (H) and an oxidizing species (OH), which are kept in combination with chlorophyll-type material. The oxidizing species can oxidize a variety of materials (characterized as H_2A) by stripping off their hydrogen. (See Figure ES-3.) In most cases H_2A is water, and the oxidizing species produces oxygen.

1	CYCLE DERIVATION	CHEMICAL PROPERTIES, THERMODYNAMICS TEMPERATURE, AND HEAT SOURCE REQUIREMENTS
2	PRELIMINARY EFFICIENCY ASSESSMENT	THERMODYNAMICS, EQUILIBRIUM CALCULATIONS SEPARATION, AND RECYCLING ESTIMATES
3	PRELIMINARY WORKABILITY ASSESSMENT (Stepwise)	LABORATORY TRIALS – REAGENTS YIELDS, ANALYSES, EQUILIBRIUMS, RATES
4	LABORATORY RECYCLING (Stepwise)	TESTS WITH RECYCLED MATERIALS, YIELDS, ANALYSES, RATES, SEPARATIONS
5	PRELIMINARY OPERATING CONDITIONS	TEMPERATURES, PRESSURES, FLOW RATES
6	DETAILED EFFICIENCY DETERMINATION	ABOVE INFORATION PLUS ASSUMPTIONS ON HEAT TRANSFER
7	CONTINUOUS, BENCH-SCALE OPERATION (Step/Cycle)	INITIAL DESIGN DATA, MATERIALS COMPATIBILITY
8	FLOW SHEET ENGINEERING ANALYSIS	"SUBSTITUTE" CHEMICAL PROCESS EQUIPMENT
9	PROCESS DEVELOPMENT UNIT	GATHER DESIGN DATA FOR PILOT PLANT
10	PILOT PLANT	

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Figure ES-2.   REQUIREMENTS FOR TECHNOLOGICAL DEVELOPMENT IN THERMOCHEMICAL HYDROGEN PRODUCTION

$$H_2O \xrightarrow[\text{Chl}]{\text{light}} \begin{cases} (H) \to \begin{cases} CO_2 \\ CH_2O \end{cases} \\ (OH) \to \begin{cases} A \\ H_2A \end{cases} \end{cases}$$

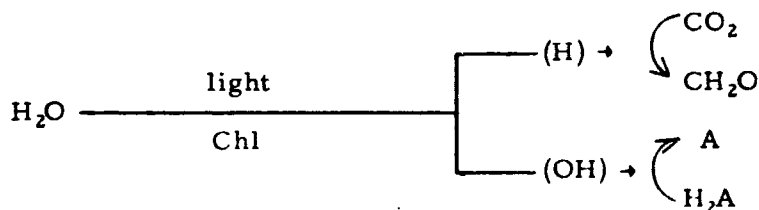Figure ES-3.   A SIMPLE PHOTOSYNTHESIS PROCESS

The reducing species has a reducing power stronger than that of hydrogen; thus the photosynthetic process is thermodynamically capable of producing hydrogen and oxygen from water.   In natural green plants, however, it appears that the reducing power so generated is always used for the reduction of carbon dioxide to carbohydrates (CH_2O) and other cell materials.

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Certain bacteria and algae contain enzymes, such as hydrogenase and nitrogenase, which are capable of catalyzing the reduction of hydrogen ions (H^+) to molecular hydrogen (H_2). Such organisms do in fact produce hydrogen under certain conditions. Thus, the biological mechanisms required for producing hydrogen and oxygen from water exist in natural organisms, but only in completely separate systems. The question is whether or not, and how efficiently, the two functions can be coupled and controlled to split water directly.

In this study we reviewed the literature pertaining to the possibility of modifying the photosynthesis process to achieve the production of hydrogen. Proposals for direct water splitting by photosynthesis processes are basically in the realm of exploratory research, and objective engineering evaluations are not possible at this time. However, we have found considerable (but not universal) optimism among experts in this field that photosynthesis can potentially be used as a method for hydrogen production, but not in the near future. All acknowledge that breakthroughs will be required; but most agree that the effort is worthwhile, even if unsuccessful, because of the fundamental importance of understanding photosynthesis (e.g., for vegetable food production).

It is obviously possible to produce hydrogen and oxygen from water by anaerobic fermentation or by photosynthetic bacteria. Such processes have been proposed, and fermentations based on species of clostridial bacteria actually have been carried out commercially. However, hydrogen is produced in such processes only as a by-product to the primary production of alcohols, ketones, or fatty acids. Presumably, better strains of bacteria could be developed to maximize hydrogen production.

A number of other biological approaches in which hydrogen might be produced by natural photosynthetic systems have been suggested:

● The genetic improvement of certain nitrogen-fixing algae species in which the biological functions for both water splitting and ammonia (or hydrogen) production co-exist, but in separate cells. In the absence of nitrogen gas and with the proper nitrogenous nutrients supplied, such species can produce hydrogen and oxygen from water.

● Direct coupling of bacterial hydrogenase with the intact photosynthetic apparatus extracted from algae or green plants and contained in an artificial apparatus ("in vitro"). The scientific feasibility of this approach has been demonstrated in the laboratory. However, two major problems

remain. The hydrogenase activity is destroyed by oxygen, and the catalytic life of the intact photosynthetic apparatus "in vitro" is very short (minutes).

- Two stage coupling in which the aerobic and anaerobic functions occur in separated processes. In the first stage, water splitting is carried out with the intact photosynthetic apparatus extracted from algae to produce a stable reductant other than carbohydrate. The stable reductant is then separated and reacted with hydrogenase in a second stage. The scientific feasibility of this concept has also been demonstrated in the laboratory, with a fairly complex biological chemical. A simpler stable reductant is needed, and catalyst life remains the primary problem.

When the photosynthetic part of a natural organism is separated from the self-repairing environment of the living state, the photocatalytic life of these complex systems tends to be very short. Although some progress has been made toward stabilization or protection of these systems, a major research effort will be required before successful application can be expected.

On the basis of current knowledge, nonbiological photolysis does not appear promising. However, exploration of the potential of this approach has not been extensive; and the field is open for exploratory research. It is our feeling that exploratory synthetic work in this area, guided by parallel research on the mechanisms of photosynthesis, will be fruitful.

The theoretical model of photosynthesis suggests that 6 quanta of light are required to split one water molecule and to carry out all of the related intermediate steps. Practical considerations suggest that 10 quanta will, in fact, be needed, corresponding to an energy efficiency of 22%. Because only one-half of incident sunlight is in the wavelength range required for photosynthesis, overall efficiencies of about 10% appear to be the maximum achievable. There is thus a possibility that the currently obtained photosynthetic efficiencies of from 1% to 2% could be significantly improved through research.

Hydrogen Production From Waste Materials

Cellulosic wastes can be converted to a variety of fuels by four different primary routes: 1) partial oxidation, 2) high-temperature reactions with steam, 3) pyrolysis, and 4) fermentation. In the first three cases, the initial process is one of gasification. Once a raw gas has been produced, a fairly conventional "clean up" process could be designed to produce pure hydrogen.

Considerable research to develop commercially viable processes for the production of SNG, liquid hydrocarbons, or alcohols from wastes is already under way. There seem to be little or no effort applied to the production of hydrogen. However, the problems being addressed primarily concern the initial conversion of the raw waste to "raw gas" and result from the considerable variation in feedstock "quality," which in turn produces a highly variable raw-gas composition. For this reason, processes entering the commercial-application stage have, for the most part, been limited to those in which the raw gas is simply used as a boiler fuel, often added to a conventional fuel supply such as coal, oil, or natural gas. Should an acceptable waste-gasification process be developed, its modification to produce hydrogen would be possible. There is little incentive at this time to research processes in which the production of high-hydrogen-content raw gas in the gasifier is emphasized.

In the case of fermentation processes, the problems are similar to those described in the section on photosynthetic hydrogen production. Currently available fermentation processes preferentially produce methane, alcohols, or carbon dioxide.

Hydrogen Production Using Fusion Reactors

In 1972, some researchers with the Atomic Energy Commission noted that water is split by ultraviolet light at high altitudes in the atmosphere and suggested that a "fusion torch" — an ultraviolet beam produced by the energy from a fusion reactor — be used to produce hydrogen. They concluded that thei. ᵣ ᵃs would require less energy per pound of hydrogen produced than electrolysis. No experimental work has been done on this concept.

KMS Fusion, Inc., of Ann Arbor, Mich., has been experimenting with laser-energized fusion reactors and has investigated processes for splitting water through chemical-reaction sequences in which certain reactions are driven by fusion-produced 14-MeV neutrons. The successful development of such a process would enable hydrogen to be produced by nuclear fusion without the intermediate production of heat. KMS claims that it can produce hydrogen; but the process itself is proprietary, and the experimental results are unpublished.

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Direct Thermal Decomposition of Water

At sufficiently high temperatures, water (steam) will undergo appreciable dissociation into its elements, hydrogen and oxygen. This is a direct decomposition via one reaction step:

$$H_2O(g) \rightarrow H_2(g) + 1/2O_2(g)$$
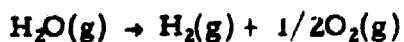
At equilibrium, the extent of this thermal decomposition depends primarily upon the temperature, but also upon the pressure, of the steam-hydrogen-oxygen system.

The decomposition of water by heat suffers from two limitations. One is the equilibrium between water and hydrogen, which necessitates temperatures above $2500^\circ C$ for production of appreciable quantities of hydrogen. The other is the separation required to obtain hydrogen and oxygen in separate streams. The energy theoretically required for this process is quite considerable and increases as the temperature increases.

Survey of Patented Hydrogen-Production Processes

To complete the survey of hydrogen-production processes, we examined the literature with the hope of finding novel processes that had been suggested, but had never been fully developed. We anticipated that, in the past, the ease of making hydrogen by steam reforming relatively cheap natural gas would have made the development of other hydrogen processes unattractive; but that now, with natural gas rapidly becoming in short supply, these processes might be worthy of attention.

A search of this type ideally would involve a complete literature review and evaluation. However, the number of literature entries on hydrogen production is immense, and a comprehensive literature search of all published literature was not practical. We proceeded on the assumption that a novel hydrogen production method, if it had not been developed, would have at least been patented.

We conducted a patent search through abstracts of patents published in Chemical Abstracts from 1917 to 1974. We limited our attention to those processes that made either pure hydrogen or significant amounts of hydrogen mixed with nitrogen, carbon monoxide, and/or carbon dioxide because these mixtures could be easily converted to pure hydrogen. Recovered abstracts

were screened and assigned to one of the 12 categories shown in Table ES-3.
Surprisingly, no promising hydrogen-production techniques that are not
already being developed were uncovered by the patent search.

Table ES-3. CATEGORIES FOR PATENTS DEALING WITH HYDROGEN PRODUCTION

Category No.	Process	No. of Patents
1	Electrolysis of pure water	128
2	Electrolysis of impure water	47
3	Electrochemical photolysis	0
4	Coal and water	394
5	Other fossil fuels	994
6	Synthesized chemicals	29
7	Thermochemical processes	10
8	Biosynthesis	9
9	Photosynthesis	0
10	Direct use of solar energy	2
11	Rejected (not a process)	500
12	Others	157
Total		2270

Pipeline Transmission of Hydrogen

Several techno-economic studies have been published on the use of pipe-
lines for transmission of hydrogen. A natural gas pipeline system consists
of a series of compressor stations placed at intervals of from 60 to 100 miles
along a pipe, and it is assumed that the same principles will be applied to the
transport of hydrogen.

In the case of a hydrogen pipeline, a question arises as to the best source
of fuel for the compressors. Some studies have assumed electrically driven
compressors, some have assumed hydrogen-fueled engines, and some have
assumed use of the same fuel (natural gas) that is conventionally used for
compressors on a natural gas pipeline. The transmission cost of natural gas
is far lower when natural gas is used to drive the intermediate pipeline com-
pressors than when the compressors are electrically driven; but, of course,
natural gas will not be available for use with a hydrogen pipeline.

In the likely case that hydrogen from the pipeline is used to run the com-
pressors, the costs are predicted to be on the order of from 3¢ to 5¢/million
Btu-100 miles for the largest (48-inch diameter) pipelines. These costs may
compared with typical natural gas transmission costs of from 1¢ to 2¢/million
Btu-100 miles.

The availability of compressors and drivers for hydrogen transmission is somewhat questionable. Reciprocating compressors could be used for hydrogen-pipeline service. Many reciprocating-compressor installations are handling hydrogen in other applications under various conditions of pressure, temperature, water-vapor content, and corrosiveness. Compression cylinders would need to be quite large to transport large pipeline quantities of gaseous hydrogen, but these large machines could be made available. One problem with using such a compressor for pipeline service would be obtaining an engine driver of sufficient power and rpm.

Turbocompressors have been designed and are currently operational for high throughputs of gas, but such high-throughput operations have never been combined with high operating pressures. Hydrogen-fueled gas turbine drivers could be used to power centrifugal compressors; however, this technology is unproved for industrial applications. Other types of compressors — including the axial, regenerative, and screw compressors — could be used for hydrogen-transmission service, but they require engineering development.

The potential problem of direct hydrogen attack on metals, referred to as hydrogen embrittlement, is of considerable concern. Hydrogen embrittlement is the degradation of mechanical properties due to the absorption of hydrogen at the surface and into the structure of a metal.

Recently, work was undertaken by the Battelle Memorial Institute to determine whether or not hydrogen embrittlement of pipeline materials would be a significant problem in a hydrogen-energy system. This work indicated that hydrogen-induced problems (hydrogen stress cracking, loss of metal ductility, and hydrogen-environment embrittlement) could be expected in the operation of a hydrogen pipeline system only in the areas of the pipe that have abnormal properties, such as hard spots (concentrations of high-strength material) or hard-weld zones; that have certain defects or other stress raisers (such as abrupt changes in direction); or that are subjected to excessively high stresses.

Pessimism because of anticipated materials problems in the pipeline transmission of hydrogen conflicts with actual operating experience. Two industrial hydrogen pipelines (one in Texas and the other in Germany), constructed of conventional pipeline materials, have been operated without major failures, although somewhat lower pressures than are found in

conventional gas lines (200 psi rather than 700 psi) are employed. There is considerable need for research to resolve the questions surrounding the compatibility of conventional pipeline and compressor materials with hydrogen gas under proposed operating conditions.

Storage of Hydrogen

Storage capability is needed in any energy-delivery system for two fundamental reasons: 1) to match the seasonal variations in demand with the economic requirements for a steady rate of production and transmission and 2) to accommodate temporary interruptions in production and transmission. There are three ways in which hydrogen might be stored in large quantities: 1) as a compressed gas in pressure vessels, underground cavities, or in pipelines (linepack); 2) as a metal hydride; and 3) as a cryogenic liquid.

The unit capital-cost and energy expenditures for large storage systems of different types are compared qualitatively in Table ES-4. As shown, between periods of peak demand a hydrogen supplier would find it most convenient to store hydrogen under compression in pipelines — but this is a relatively low capacity technique. The next most convenient form of storage is in an underground cavity. Preliminary indications are that hydrogen can be stored underground just as is natural gas. However, this storage technique has not been demonstrated for pure hydrogen.

Table ES-4. HYDROGEN STORAGE

Technique	Energy Expenditure	Expected Capital Cost
Linepack	Low	Low
Underground	Low	Low
Liquefaction	High	High
Metal Hydride	Medium	Medium
Compressed Gas	Low	High

Hydrogen in Gaseous Distribution Systems

Although there have been many research and development programs (recent and current) related to hydrogen energy, none has tested the conventional gas-distribution system for use with hydrogen. Additionally, hydrogen delivery through conventional (modern) gas-distribution systems has not been demonstrated, although the older systems were once used with manufactured

gas that contained up to 50% hydrogen. Very little information is available on the compatibility of present-day natural gas distribution systems with hydrogen.

The basic distribution system in most older, large cities is a low-pressure, cast-iron-pipe system. However, across the United States a great diversity of materials appears in local systems, including constructions of wrought iron, copper, steel, brass, polyethylene, PVC, rubber, lead, aluminum, and many other materials. From the diversity of equipment, operating conditions, and materials of construction, it is evident that any firm statement that hydrogen or hydrogen-rich gases can be adequately and safely delivered to the customer using the in-place natural gas distribution system is a presumption. The compatibility of the distribution system with hydrogen requires verification by demonstration.

Although no major difficulties are expected, the areas in which compatibility problems might be experienced are —

- The tripling of the volumetric flow rate to maintain the energy-delivery rate

- The additives to the hydrogen required for odorization and illumination of hydrogen flames

- The higher volumetric leakage (diffusion) of hydrogen through plastic pipes

- The higher volumetric leakage of hydrogen through porous welds, cracks, corrosion pinholes, and imperfectly sealed joints

- Line purging and maintenance (because of hydrogen's wide flammability limits and low ignition energy)

- The increase in the gas temperature upon adiabatic expansion (in this respect exhibiting behavior reverse to that of most gases).

Present Industrial Uses of Hydrogen

Hydrogen is one of the world's leading chemical intermediates and is used in many different applications. Many conflicting estimates of the total U.S. annual production of hydrogen have been published. The differences in these reports are due partly to the fact that some do not include those uses of hydrogen in which the hydrogen exists only as an intermediate product between two processes (i.e., captive hydrogen). Hence, some estimates include only

"merchant hydrogen," which is actually sold as a commodity, while others attempt to be all-embracing and include estimates not only of the amount of captive hydrogen produced, but also of the low-purity hydrogen produced (for example, in such processes as blast-furnace operation). Rather than quote figures for total U.S. hydrogen production, which would have to be carefully qualified, we have quantified estimates of hydrogen usage in each of the major areas of consumption. These are presented in Table ES-5.

Table ES-5. 1973 HYDROGEN UTILIZATION IN THE UNITED STATES

Market Segment	Input/Output Ratio, Hydrogen Product	1973 Demand, 10^{15} Btu
Ammonia, SCF/ton	69,000-78,500	0.340
Methanol, SCF/ton	52,000-75,000	0.076
Oil Refining		
Hydrotreating	Varies widely	0.176
Hydrocracking, SCF/bbl	1800-2500	0.241
Other	--	0.049

The U.S. market for merchant hydrogen (i.e., for hydrogen sold as a product, included in the classification "other") was 72 billion SCF/yr according to the U.S. Department of Commerce. The growth rate from 1973 to 1974 was 11%. This growth rate is among the highest reported for high-volume inorganic and organic chemicals.

The major markets for captive hydrogen (ammonia, methanol, and oil refining) are growing at rates that reflect the general trends of increased use of fertilizers, high-volume chemicals, and processed fuels. Major changes in the steady upward growth pattern are not anticipated; however, the increasingly scarce or costly feedstocks (petroleum and natural gas) that are used to make this hydrogen may be replaced by more plentiful energy sources such as coal or nuclear power.

We produced a conceptual design for an ammonia plant that utilizes pure hydrogen instead of natural gas, which is currently used as a feedstock. Preliminary calculations show the plant to be 78% efficient (compared with 54% for a natural-gas-fed plant). The cost of ammonia made from hydrogen (delivered at a price of $5.00/million Btu) was $155/ton. Considerable rebuilding of an existing ammonia plant would have to be undertaken if its feed were hydrogen instead of natural gas because an additional means of separating nitrogen from the air input (currently carried out by the natural gas reformer) would have to be provided.

Large quantities of hydrogen are used in the synthesis of methanol; of course, this process also requires a supply of carbon. In a case in which methanol was synthesized from coal, additional hydrogen provided from an outside source would reduce the overall coal consumption by the plant.

Large quantities of hydrogen may, in the future, be used to refine iron ores by direct reduction. These processes use a reducing gas (usually carbon monoxide and hydrogen) to reduce iron oxides to metallic "sponge" iron. The sponge iron is then further refined in an electric furnace. In the past, direct reduction has been attractive in countries in which natural gas was plentiful and coal was not. In the United States, metallurgical coal and coke are becoming increasingly expensive, and natural gas availability is decreasing. Production of a reducing gas from bituminous and lower grade coals may become attractive in the next decade. If, in the future, the reducing gas were hydrogen produced from nuclear power and water, the steel-making process would be freed from its dependence on coal. This possibility is being studied by the American Iron and Steel Institute.

At present, hydrogen is used as a fuel gas only in the unusual circumstance in which it is produced as an unwanted by-product. On the other hand, conventional industrial fuel use accounts for as much as 28% of the total U.S. energy consumption, so it is in this area that the greatest potential for industrial hydrogen utilization lies. More than half of this 28% is used to generate steam, a process that should be readily convertible to the use of hydrogen as a fuel.

In examining hydrogen's role in process-steam generation, two approaches are obvious:

1. Hydrogen-air combustion in a conventional boiler with a heat exchanger

2. Hydrogen-oxygen direct combustion with a water diluent.

The former case is basically a fuel substitution. However, the conventional oil or gas burner would have to be replaced or modified to allow it to operate properly with hydrogen. The relatively unexplored hydrogen-oxygen system requires a more drastic change. Devices that burn hydrogen and oxygen to make steam are expected to be of low capital cost, high in efficiency (> 95%), nonpolluting, and capable of very fast response. Conventional boilers are

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usually limited to an outlet temperature of 1200°F, but hydrogen-oxygen steam generators could deliver steam at temperatures of 4000°F or higher. The most obvious drawbacks of the hydrogen-oxygen system are the additional cost of delivered oxygen and the need to completely replace the original steam boiler with new equipment.

Residential Uses of Hydrogen

Hydrogen's greatest potential use is as a gaseous fuel in industrial, commercial, and residential applications. Because of the physical and combustion properties of hydrogen, residential appliances that have been designed for use with natural gas must be converted before they can operate on hydrogen fuel.

Figure ES-4 shows the parts of a representative atmospheric gas burner that is typical of those used on gas appliances. Fuel at low pressure (from 3 to 16 inches water column) is metered through a gas orifice. As the gas jet leaves the orifice, ambient air is drawn in through openings and mixes with the fuel gas as it travels down a mixing tube to the burner ports. The air-gas mixture is ignited as it emerges from the ports. The air supplied through the openings near the metering orifice is known as primary air. Ambient air that diffuses into the flame after ignition is known as secondary air.
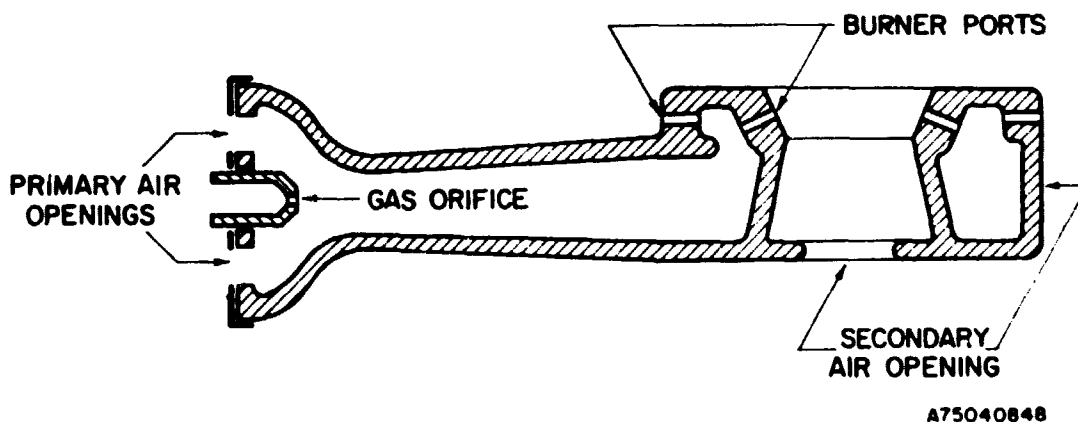

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Figure ES-4. PARTS OF AN ATMOSPHERIC GAS BURNER

Data taken from experiments with Bunsen burners operated on hydrogen show that (for Bunsen burners) the flow rate of fuel-air mixtures through the burner ports must be much higher than for natural gas or the flame front will propagate upstream, through the methane-sized burner ports, to the metering orifice. This action is known as flashback and can severely damage appliances. Flashback may be eliminated by cutting off the primary air, thus making the mixture upstream of the burner ports not flammable.

Our analysis indicates that the best approach to appliance conversion would be to design a replacement burner head, with a metering orifice, that could be installed in the field. In this way, the burner-head volume can be minimized, as can problems with ignition and extinction noises (sometimes experienced with hydrogen burners operated without primary air). It must be kept in mind, however, that the performance of real appliance burners is hard to predict from the behavior of Bunsen burners. Thus, experimental programs will be necessary before a replacement burner head can be designed.

An important feature of hydrogen combustion is that it can be made to take place on a catalyst. Because the catalytic surface is a participant in the chemical reaction sequence of combustion, the "energy barrier" between the reactants and products of combustion can sometimes be reduced. This allows the combustion to take place at lower temperatures.

When catalyzed by noble metals (the platinum family), hydrogen combustion can begin in air at room temperatures. Heat is released as the hydrogen reacts with oxygen: This heats the surface, but steady-state combustion can be maintained at surface temperatures as low as $250^{\circ}F$. (If catalytic combustion is maintained below about $2000^{\circ}F$, the formation of nitrogen oxides is, for all practical purposes, eliminated.) All other common fuels must be heated to moderately high temperatures before they will begin to combust catalytically. Materials other than precious metals can be used as hydrogen-combustion catalysts, but higher temperatures (above $500^{\circ}F$) are required to activate them.

Although low-temperature catalysts are platinum based, they will probably not be very expensive. With the loadings used in present experimental studies, about 20¢ worth of platinum is required to release 1000 Btu/hr. At

that rate, an average house would require a capital investment of about $10 to $15 worth of platinum for the catalytic burner for all of its space-heating requirements.

Catalytic appliances (space heaters, for example) do not have to vent their combustion products to the outside. Usually, 25% or more of a fuel's heat of combustion is lost with the combustion gases as they are vented. Also, catalytic igniters could be used to start flame-type combustion in the atmospheric hydrogen burners mentioned in the previous section. This would eliminate the need for pilot lights.

Use of Externally Supplied Hydrogen in Fuels Synthesis

The fundamental objective of all coal-based synthetic-fuels processes is to turn a low-hydrogen-content fuel (coal) into higher hydrogen content fuels (oils, methanol, or methane). Hydrogen is currently produced in these processes as an intermediate from coal or char and water. In some processes a great deal of the input coal (in methanol and SNG processes, about half) is used for hydrogen production.

Other than by using natural gas or oil, on-site hydrogen production from coal is the cheapest process available. However, coal is an exhaustible resource, the price of which will surely rise in the long term. There are possible sources of hydrogen that are tied to renewable or extremely large energy sources (solar or fusion) that are not likely to rise as much in cost in the long term. Thus, it seems likely that at some point in the future it will be economically advantageous to reserve as much coal as possible for synthetic-fuels production and utilize some "outside" source of hydrogen. We have investigated this possibility during the course of this study. We have focused our attentions on "retrofitting" developed synthetic-fuels processes to accept outside hydrogen because the synthetic-fuels industry is likely to be well established, with great investments in process-plant equipment, before outside hydrogen becomes economically attractive.

The processes for making fuel oils, methanol, and methane from coal and for making synthetic crude oil from oil shale were investigated, and the estimates of maximum possible outside-hydrogen usage are shown in Table ES-6. In most cases, these processes already contained a "hydrogen plant," and most of the estimated demand for outside hydrogen stems from replacement of the hydrogen plant with a hydrogen source.

Table ES-6. DEMAND FOR OUTSIDE HYDROGEN IN TYPICAL
SYNTHETIC FUELS PROCESSES
(Per Unit Product Basis)

Process	Hydrogen Demand
SNG From Coal (Lurgi Process)	1 SCF of hydrogen/SCF SNG
Methanol From Coal	42,000 SCF/ton of methanol
Syncrude From Coal (CSF Process)	5800 SCF/bbl of syncrude
Coal Syncrude Refining	1500 SCF/bbl of gasoline
Syncrude From Oil Shale	1300 SCF/bbl of syncrude
Oil Shale Syncrude Refining	700 SCF/bbl of gasoline

We determined parametrically, for a given price of coal, the point at
which it makes sense economically to use outside hydrogen. For example, at
a coal cost of $2.00/million Btu, auxiliary hydrogen supplies become econom-
ically attractive at $2.50/million Btu and at $5.00/million Btu for SNG-
gasoline production and for methanol production, respectively. Thus, pro-
vision of nuclear-based electrolytic hydrogen to a present-technology coal-to-
methanol plant is already almost economically justified. The cost break-even
relationships are shown in Figure ES-5.
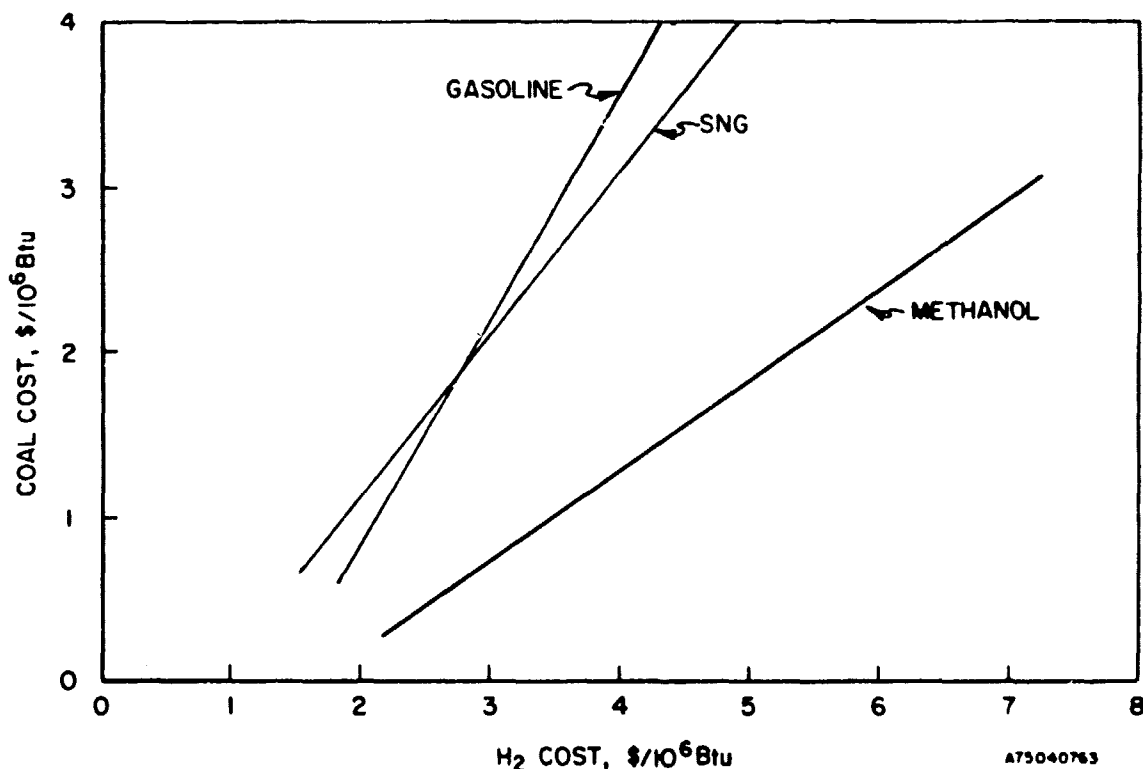
Figure ES-5. BREAK-EVEN COSTS FOR SYNTHETIC FUELS PRODUCTION
FROM COAL AND COAL-PLUS-HYDROGEN PROCESSES

Research and Development Recommendations

In this section we summarize a hydrogen research and development program. The intent of this program is to develop branches of hydrogen-related technology, with the aim of eventually introducing hydrogen on a large scale. There is already a considerable amount of research being done on hydrogen by government and industry. Our recommendations, based on our best information about current activities, are for additional programs in areas in which no work, or insufficient work, is now being done. If the programs we recommend here are to have their maximum beneficial impact, they should be completed within the next 5 years.

Hydrogen Production

Electrolysis

Research in the area of electrolysis should be conducted on catalysis, electrode structure and materials, new separators, and electrolytes. This research should be divided into basic research on electrode structure and gas evolution and applied R & D on other topics that should be conducted on both alkaline and ion-exchange cells. A reasonable research objective would be operation at about 1.5 volts and at a current density of about 500 A/sq ft in a piece of equipment with a total capital cost of between $50 and $100/kW input.

Coal Gasification

There is a great deal of research and development work going on in the area of the gasification of coal to produce both low-Btu and high-Btu fuel gases. This research, funded by government and industry, deals with the initial gasification steps that convert coal to a raw-gas product. Subsequent treatment and purification of this raw gas to make pipeline gas, boiler fuel, or pure hydrogen is largely a matter of selecting from equipment that is already at a high level of development.

We feel that the development of processes that make pure hydrogen from coal can benefit greatly from this ongoing R & D, and therefore large research programs to develop these processes are not needed. We do suggest, however, that a low-level effort be addressed to the development of flowsheets and calculations of systems costs and efficiencies. This would allow for

selection of the proper primary gasifiers in the design of pure hydrogen-from-coal plants. The level of effort could be quite modest, as long as the very substantial coal-gasification programs are continued for other applications.

Thermochemical Methods

Efforts should be directed toward finding more efficient cycles that operate with noncorrosive reactants. These programs should eventually develop kinetic data and heat and material requirements for the specific cycles that are identified as the most promising. Of particular importance is the identification of suitable energy sources, other than nuclear reactors, for thermochemical hydrogen production. The prospects for solar-driven cycles deserve considerable attention.

Integrated Nuclear-Electrolytic Facility

A short study is needed to determine the cost-effectiveness and efficiency of a nuclear-powered electrolytic plant designed specifically for hydrogen production. Better comparisons with proposed thermochemical processes (HTGR driven) can then be made.

Photosynthesis

Photosynthetic hydrogen production is very promising for the long term; thus, the appropriate research would seem to be both basic and long range. The probability of success would be proportional to the number of individual creative scientists involved, rather than to the total manpower or money invested. In particular, colloid, catalysis, electrochemistry, and ligand field theory and engineering theory may be helpful. The long-range nature of the program should be recognized, and funding should be continuous.

Solar-Photovoltaic Production

The production of hydrogen by the photovoltaic conversion of solar energy should also be investigated. Conceptual design studies should be conducted to provide the technical and economic data needed for comparisons with other processes.

Application of Controlled Thermonuclear Fusion

A short feasibility study is needed to assess the practicality of using ultraviolet light beams to split water. Further R & D should be recommended if the concept shows merit.

These R& D recommendataions for hydrogen production are summarized in Table ES-7.

Table ES-7. R & D RECOMMENDATIONS FOR HYDROGEN PRODUCTION

Method of Production	Average Annual Funding per Program, $1000	Years Pursued	No. of Programs	Five-Year Total Funding, $1000	Description
Electrolytic	500-1000	5	1-3	2,500-15,000	Basic research and cell development
Thermochemical	750-1000	5	3-4	11,250-20,000	Cycle derivation, analysis, and testing
Coal Gasification	100-200	2	2	400-800	Survey-related technology
Photosynthetic	50-200	5	5-7	1,250-7,000	Small experimental programs
Integrated Nuclear-Electrolytic	50-100	2	2	200-400	Optimum-process description
Solar-Photovoltaic	50-100	3	3	450-900	Lab studies
Fusion-Based	50-75	2	1	100-150	Feasibility studies

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Hydrogen Delivery

Pipeline-Material Compatibility Evaluation

The question of whether hydrogen can be transmitted through existing natural gas lines or whether new pipelines will be needed because of materials problems should be answered immediately. Studies should investigate hydrogen-related problems such as the loss of metal ductility, hydrogen stress cracking, and hydrogen-environment embrittlement in pipeline steels. Further research will be needed for solutions should the problems prove serious.

Transmission Experimental Feasibility and Cost Studies

If hydrogen-environment embrittlement proves to be a manageable problem in pipelines, an investigation into the behavior of other gas transmission system equipment with hydrogen should be initiated. Concurrently, the economic feasibility of hydrogen transmission should be investigated.

Pipeline-Compressor Evaluation

Early studies of hydrogen pipelining have shown a great divergence in opinion on the subjects of hydrogen compressors and the units that will drive

them. A small-scale study could determine the best compressor-prime mover combination.

Behavior of Hydrogen in Gas Distribution Equipment

There is a dearth of information on the behavior of hydrogen in existing natural gas distribution lines and related hardware. Experimental studies should be conducted to determine the problems that may be encountered when meters, regulators, and the various nonferrous pipe materials in natural gas distribution systems are exposed to hydrogen.

Underground and Hydride Storage of Hydrogen

Preliminary feasibility studies, of a theoretical and experimental nature, on the effects of the presence of hydrogen on the mechanisms of gas sealing should be started.

The storage of hydrogen in the form of metal hydrides may be important not only for mobile applications, but also for electric-utility peakshaving. New alloys are still being identified. Support for several laboratory efforts should be continued.

Improved Cryogenic Systems

The possibility of liquid-hydrogen transmission should also be studied, especially in the context of integrating it with superconducting or "cryo-resistive" cables for electric-power transmission.

Hydrogen Odorants and Illuminants

Because hydrogen gas is odorless and its combustion is nonluminous, odorants and illuminants will have to be added to the gas. The identification of suitable odorants and illuminants is not a pressing task that demands immediate attention; however, it should be undertaken sometime during the next 5 years.

Recommendations for hydrogen-delivery R & D are summarized in Table ES-8.

Hydrogen Utilization

By Industry

Our study has identified at least five large industrial processes that are potential users of hydrogen: 1) the direct reduction of iron ores, 2) ammonia

Table ES-8. RECOMMENDATIONS FOR HYDROGEN DELIVERY

Topic	Average Annual Funding per Program, $1000	Years Pursued	No. of Programs	Five-Year Total Funding, $1000	Description
Hydrogen Embrittlement	300	2	2	1200	Define problem
Pipeline-Cost Study	100	3	1	300	Establish economics
Compressor Evaluation	100	2	1	200	Evaluate options
Transmission-Component Study	5000	1	1	5000	Experimental evaluation
Distribution-Component Study	300	5	1	1500	Experimental evaluation
Underground Storage	75	2	2	300	Feasibility study
Metal Hydrides	200	5	3	3000	New hydrides
Improved Cryogenic Systems	75	5	2	750	Pursued with industry
Odorants and Illuminants	50-75	2	2	200-300	Find additives

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synthesis, 3) methanol synthesis, 4) process-steam generation, and 5) the production of synthetic fuels from coal. Although these markets for feedstock hydrogen are not as large as the market for gaseous fuel, they deserve special consideration because their economics may allow them to use hydrogen of a higher cost than can the fuel market. Thus, these markets may be the first to accommodate hydrogen technology — even while new, low-cost methods of hydrogen production are still being developed. (This is especially true of ammonia synthesis.)

Feasibility studies, in greater depth than those done in this study, should be conducted to determine the conditions under which it will be economical to use "outside" hydrogen in these processes.

Development of Hydrogen-Fueled Burners and Appliances

The assessment of the adaptability of present-day appliances to hydrogen fuel has not really progressed far beyond the discussion stage. Experimental studies to determine the necessary conversion parts and procedures should be started soon.

Work on the development of catalytic appliances has been insufficient. Better catalysts (both high and low temperature) and improved burner configurations are needed, and practical prototype appliance models should be developed. Because the work is still in a highly creative stage, multiple efforts — perhaps as many as four — should be begun.

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As a Natural Gas "Extender"

Besides the across-the-board conversion of all gaseous-fuel equipment to hydrogen within given areas, hydrogen might also be used as a gaseous fuel by blending it with natural gas supplies. A proper role for governmental research would be a study of the legal and institutional implications (requiring regulatory-agency action) of such a use of hydrogen.

By-Product Credits

A potential-market study should be initiated cn the use and value of the oxygen produced as a by-product during hydrogen manufacture. Broad studies should be made on an industry-wide basis, perhaps by the government; but detailed equipment development should probably be done by existing large-scale suppliers of oxygen.

Table ES-9 shows the R & D programs recommended for hydrogen utilization. The funding totals for research on hydrogen production, delivery, and utilization are shown in Table ES-10.

Table ES-9. R & D RECOMMENDATIONS FOR HYDROGEN UTILIZATION

Topic	Average Annual Funding per Program, $1000	Years Pursued	No. of Programs	Five-Year Total Funding, $1000	Description
Industrial-Feasibility Studies					Detailed feasibility studies
Ammonia	75	1	1	75	
Methanol	75	1	1	75	
Synthetic Fuels	100-150	2	1	100-300	
Steam Generation	100	2	2	400	
Direct Reduction	100-150	1-2	1-3	100-900	Some experimental work
Burner Development					
Appliances	250	2-3	2-4	1000-3000	Experimental designs and evaluations
Catalytic Combustion	100-250	5	2-4	1000-5000	Several programs
Hydrogen-Natural Gas Additive	100	5	1	500	Study of regulations
By-Product Credits	100	2	1	200	Oxygen utilization

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From the results of the study, we believe that there are no major technical reasons for hydrogen not becoming a key component of the U.S. energy system in the future. However, during the course of this study we found numerous instances in which the ultimate potential of the hydrogen-energy system is unclear because some elements were not sufficiently developed.

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Table ES-10.   FUNDING TOTALS FOR HYDROGEN R & D
(5 Years)

Sector	Low	High
	— $1000 —	
Production	16,150	44,250
Delivery	12,450	12,550
Utilization	3,450	10,450
Total	32,050	67,250

Many technologies that are still only conceptualizations or laboratory-scale projects could significantly lower the delivered cost of hydrogen or increase its usage.   The two levels of funding in Table ES-10 reflect the option of minimum recommended funding for the minimum number of recommended programs versus a maximum funding level per program, including some parallel and simultaneous efforts.   Primarily, the difference between the $32 million and the $67 million figure is due to multiple program efforts. For example, in thermochemical hydrogen production, several programs to examine different cycles could be funded simultaneously.   Another example is photosynthetic hydrogen production, a case in which several different general approaches appear to have merit at this time and in which individual creativity is of great importance.

Through these programs we will be able to investigate, in a thorough and logical manner, the hydrogen option for future energy delivery.   Without the additional funding, hydrogen-energy programs will continue to progress slowly (with the current and planned level of industrial and governmental support).   In effect, prospects for the electricity option for nonfossil energy delivery will predominate in the future, primarily because of default in progress on hydrogen-energy development.   At the same time, if the hydrogen option has an unforeseen and crippling flaw, early identification of it will allow for a refocusing of efforts or for abandonment of the hydrogen option for good reason.   The funding is needed very soon.   Waiting for the need (domestic energy deficit) to develop further will deprive us of the lead time required for development, demonstration, and commercialization of a suitable energy-delivery system.